Arch. Min. Sci. **65** (2020), 2, 241-254

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2020.133190

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ECONOMICS OF COMBINED CO_2-EOR AND CCS PROJECTS BASED ON THE EXAMPLE OF A POLISH MULTILAYERED OIL FIELD

The article presents a comprehensive economic analysis of a CO_2 injection project in one of the Polish oil fields for both increased production (CO_2-EOR) and underground storage (CCS). An interesting differentiator of this work is the use of a multilayered reservoir, which is actually not one reservoir but several located in the same place, as an example. It allows the optimization of the processes of injection, production and storage. Such projects are becoming more and more important because recently, after a period of long-term stagnation, costs of carbon allowances have started to rise which affects e.g. the electricity market in Poland. This can be an important incentive for the development of CCS technology, especially in combination with CO_2-EOR. In the case of very high costs of carbon emissions rights CCS may turn out to be a cheaper solution. Economic efficiency is the main determinant of the EOR project's success, as well as a very significant factor influencing the potential development of CO_2 underground storage. Results are based on the numerical simulation of a combined CO_2-EOR and CCS project. This analysis has been divided into two parts. The first uses a standard, deterministic approach, based on the DCF method and NPV indicator. It also provides a detailed sensitivity analysis, with particular reference to the impact of oil prices and the cost of carbon emissions rights on a project's profitability. The second part of the economic analysis is probabilistic and involves estimating the maximum amount of CAPEX using the Monte Carlo method. Two cases were taken into account. The first assumes that the CO_2 emitter pays for CO_2 storage and the price is equal to 80% of the emissions rights price (with storage revenue). In the second one the emitter does not pay for storage (without storage revenue).

Keywords: CO_2-EOR, CCS, oil field, carbon price, profitability

1. Introduction

Typically, the life-cycle of an oilfield consists of three phases: primary, secondary, and enhanced oil recovery (EOR). During the first phase – primary recovery – the original reservoir

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pressure is the main force used to produce reservoir fluids. Gradually, however, reservoir pressure (reservoir energy) decreases and therefore production rates fall. Usually, the oil recovery factor related to primary production is between 10% and 20% of the original oil in place (OOIP) [1]. The second phase – secondary recovery – is the process of fluid injection, using injection wells, whose aim is to maintain reservoir pressure and increase production. Water is the most common injectant for secondary recovery because of its availability and low cost; thus the process is often described as waterflooding [2]. Cumulative oil recovery achieved as a result of this process remains between 30% and 50% of the OOIP [3].

Enhanced oil recovery (EOR) is a group of different techniques which enable production of hydrocarbons not produced during the primary and secondary phases. EOR methods can be divided into several groups – thermal, chemical, gas injection, microbiological and others. One of the gas injection techniques is carbon dioxide enhanced oil recovery (CO_2-EOR).

The CO_2-EOR method is used to increase oil production by injecting CO_2 into the reservoir. Injected CO_2 mixes with oil, which facilitates the movement of reservoir fluids and therefore increases oil production. CO_2-EOR can give additional production of from 5% to 20% of the OOIP [4]. Most of the CO_2 injected into the reservoir for EOR remains trapped underground which is typical of EOR operations. It makes them potential candidates for carbon capture and storage projects. The main purpose of carbon capture and storage (CCS) is to reduce emissions of greenhouse gases into the atmosphere. However, combining CCS with CO_2-EOR may provide an important financial incentive to develop CCS projects [5].

Currently CO_2 is an expensive input for CO_2-EOR projects, and therefore the amount of CO_2 is usually economized. However, in the context of carbon emissions policy, such projects may receive additional revenues for the amount of CO_2 they sequester [6]. This is especially advantageous when compared to the cost of standalone CCS projects [5]. CO_2-EOR may be a very interesting option for CCS projects because it can provide additional profit [4]. Additionally, hydrocarbon reservoirs are good candidates for CO_2-EOR because a lot of geological and production data is available and also most of the infrastructure already exists [6].

The IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project is an example of successful combining of the EOR method and CO_2 storage. It is located in southeast Saskatchewan in Canada and it was launched in 2000 at Weyburn and in 2005 at Midale. Now it is the world's largest geological storage site of CO_2 where about 2.8 million metric tons of CO_2 are stored each year. Up to now over 30 million metric tons of anthropogenic CO_2 have been stored in both fields. The source of CO_2 for this project is the Great Plains Synfuel plant in Beulah, North Dakota. CO_2 is transported via pipeline 180 miles north to the Weyburn and Midale fields. The total amount of CO_2 which is to be stored there is 40 million metric tons – 30 million at Weyburn and 10 million at Midale [7].

An idea of combining and co-optimization of CO_2-EOR is becoming more and more popular among engineers and scholars resulting in a growing number of publications addressing this issue e.g. [8-17] and many others.

As mentioned above, combining CCS and CO_2-EOR can provide additional profits for the operator of the oilfield. In Europe additional income may be taken into account thanks to the European Emission Trading Scheme (EU ETS) which is the largest carbon market in the world, covering about 11,000 CO_2 emitting installations . In this system a single, EU-wide cap on emissions has been applied and it has shifted from free allocation to auctioning [18]. The EU has adopted a combination of climate targets and policies for both 2020 and 2030. The 2020 package consists of three key targets: a 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewable energy sources and a 20% improvement in energy efficiency. For 2030, these targets are: a 40% cut in greenhouse gas emissions (compared to 1990), a 27% share of renewable energy consumption and 27% energy savings compared to the business-as-usual scenario [19].

The rationale for such a system is that emissions trading allows us to achieve emission reduction targets in an efficient and effective way [20]. Under this system, the emitters can buy and sell carbon emissions rights and the main incentive is the difference between their price and the cost of carbon reduction technology [18].

Fig. 1. Historical prices of European carbon emissions rights
Source of data: [21]

Figure 1 shows the prices of carbon emissions rights in the EU over the last 10 years. Recently, after a period of long-term stagnation, these prices have started to grow, which affects the electricity market in Poland. This can be an important incentive for the development of CCS technology, especially in combination with CO_2-EOR. In the case of very high prices of carbon emissions rights CCS may turn out to be a cheaper solution. In Poland, there are many oil reservoirs that have been operating for a long time, mainly with primary methods, and have great potential for the use of combined CCS and CO_2-EOR [22,23] and [24].

The article presents a comprehensive economic analysis of a CO_2 injection project in one of the Polish oil fields for both increased production (CO_2-EOR) and underground storage (CCS). An interesting differentiator of this work is the use, as an example, of a multilayered reservoir, which is actually not one reservoir but several such structures located in the same place. It allows the optimization of the process of injection, production and storage.

2. Description of the oil field and the simulation model

The oil field, which is an example of combined CO_2-EOR and CCS, is located in southern Poland and belongs to flysch Carpathians (Silesian Unit). It is situated within the western extension of a bigger anticline and represents a layered type of reservoir. It has been producing for over 100 years with a recovery factor of 16.72% (only primary production) and its characteristics lend it to the use of a combined CO_2-EOR and CCS approach. That field has already been the subject of preliminary investigations, carried out by the team to which the author belongs, and their results are described in [25].

A numerical model of the field, based on real data, contains 8 horizons which are hydrodynamically independent. The 5 shallowest horizons are saturated with oil and the 3 remaining are gaseous. During the production period the pressure of the oil horizons fell below saturation pressure, therefore gas caps were formed there.

A simulation of combined CO_2-EOR CCS was made using 5 injection wells. Their locations and a vertical intersection of the reservoir are shown in Fig. 2.

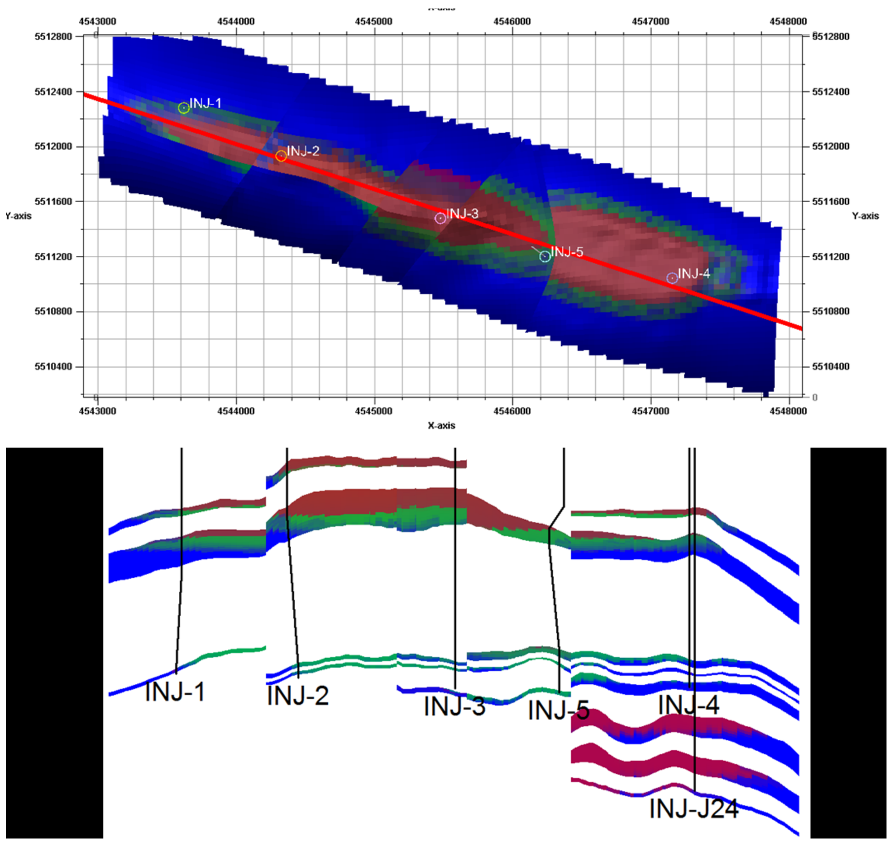

Fig. 2. Injection wells and vertical intersection of the reservoir
Source: [23]

CO_2 injection scheme is as follows:

- Injection starts from the lowest oil horizon and it is continued until the average pressure in that horizon reaches the initial pressure level.

- When this condition is met, the horizon is closed and the next horizon (lying above) is opened .
- The maximum limit of CO_2 content in natural gas extracted from the reservoir is set at 7.5%. If that limit is met the entire flow of produced gas goes into gaseous horizons to be stored there.
- The limit of CO_2 in produced fluid for each well is set at 95%.
- Simulation timeframe was 15 years and the daily injection rate was 35 000 m^3/day.

During 15 years of simulated operation total oil production has increased by almost 350% (compared to the base case without EOR approach) (Fig. 3). The total volume of injected CO_2 was over 175 million sm^3. Fig. 4. shows that the relationship between total CO_2 injection and incremental total oil production was almost a straight line. Production of 1 sm^3 of additional crude oil required injection of 3000 to 6000 sm^3 of CO_2 (Fig. 4).

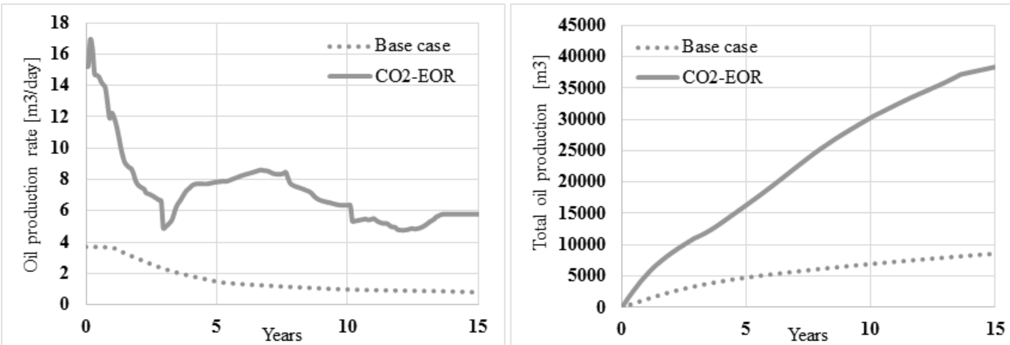

Fig. 3. Forecast profile – oil production rate and total production
Source: [23]

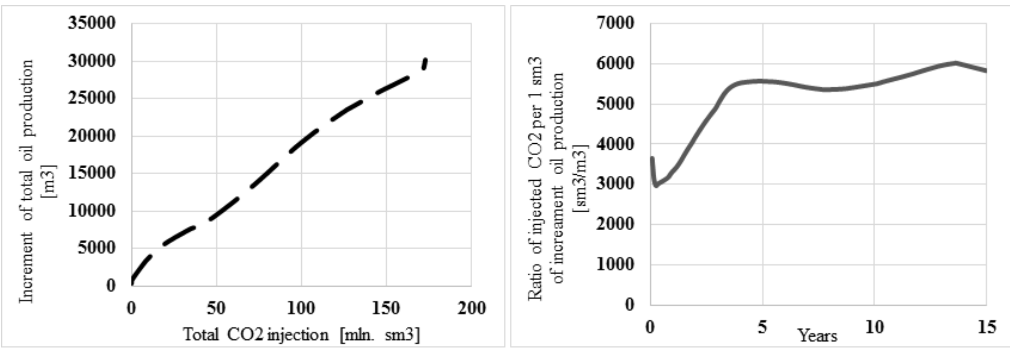

Fig. 4. CO_2 – EOR efficiency indicators during simulation
Source: [23]

Concentration of CO_2 in produced natural gas had met the limit (7.5%) after about 9 months and afterwards the process of injecting all of the produced natural gas into gaseous horizons was started. Throughout the simulation of combined CO_2-EOR CCS process the share of CO_2 in the fluids produced was increasing and some of the wells had to be shut down because of that. Fig. 5 presents CO_2 plumes in the reservoir after 15 years of simulation. More detailed, technical descriptions of the field, the simulations and their results are presented in [23].

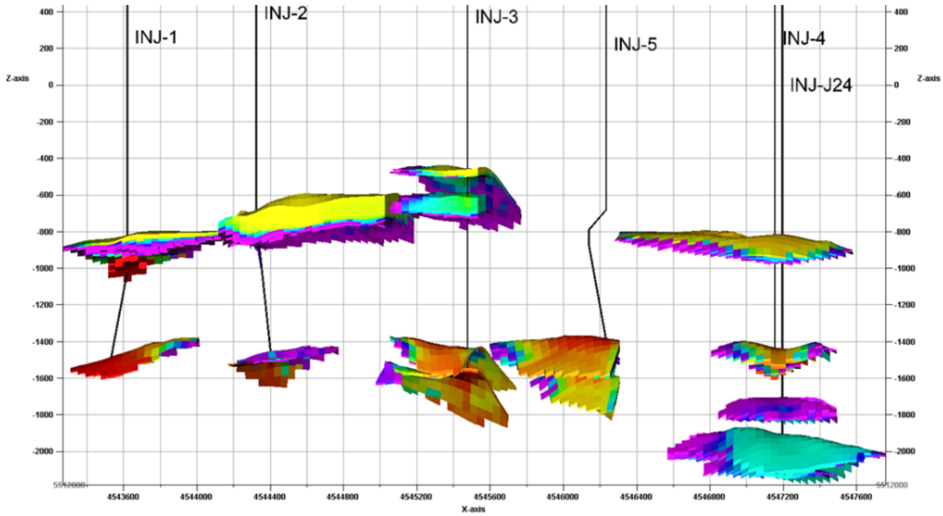

Fig. 5. CO_2 plume after 15 years of injection
Source: [23]

3. Economic analysis

Economic efficiency is the main determinant of the CO_2-EOR and CCS project's success, as well as a very serious factor influencing the potential development of CO_2 underground storage. In standard CO_2-EOR projects the cost of injected CO_2 is a very important limitation, but the combination of such project with CCS can make achievement of the profitability threshold much easier.

This article shows the results of a comprehensive economic analysis based on the numerical simulation described above. This analysis has been divided into two parts. The first uses a standard, deterministic approach, based on the DCF method and commonly used NPV (Net Present Value – cumulative sum of discounted cash flows) indicator. It also provides a detailed sensitivity analysis of such an investment, with particular reference to the impact on it of oil price and the cost of carbon emissions rights . The calculation assumes that the charge for CO_2 storage will be 80% of the purchase price of the right to emit the same volume of that gas. Table 1 shows the basic assumptions of the financial model.

CAPEX consist mainly of well workovers and surface installation expenses. When it comes to operating expenses overheads, costs of injection and produced fluid processing are the predominant cost drivers. Revenues are obtained from selling crude oil, natural gas and storage of CO_2 (only in the case of storage revenue).

TABLE 1

Basic assumptions of the economic model

Crude oil price [USD/bbl]	40-100
USD/PLN rate [-]	3,5
Discount rate [%]	6
Carbon allowance price [€/t]	20-80
CIT rate [%]	19
Depreciation rate [%]	10
Variable cost of oil production [PLN/cm]	60
Annual overhead exp.	2 000 000
Cost of CO_2 injection [PLN/Mcm]	10
Capital Expenditures (CAPEX) [PLN]	130 000 000

Free cash flow (FCF) of the project was estimated according to the formula (EBIT – earnings before interest and taxes):

$$\begin{aligned} \text{FCF} \;=\; & \text{EBIT} * (1\text{-Tax Rate}) + \text{Depreciation \& Amortization} + \\ & - \text{Changes in Working Capital} - \text{Capital expenditure (CAPEX)} \end{aligned}$$

Figure 6 shows the NPV of the project versus the price of carbon emissions rights and the price of crude oil. It can be clearly seen that for the price of carbon emissions rights below €35/t and oil prices in the range of 40-100 USD/bbl the project is unprofitable. On the other hand, if the price of carbon emissions rights is above €40/t it makes such a project profitable, almost irrespective of the price of crude oil. This observation is confirmed by the sensitivity analysis of the NPV, the results of which are presented in figures 7 and 8.

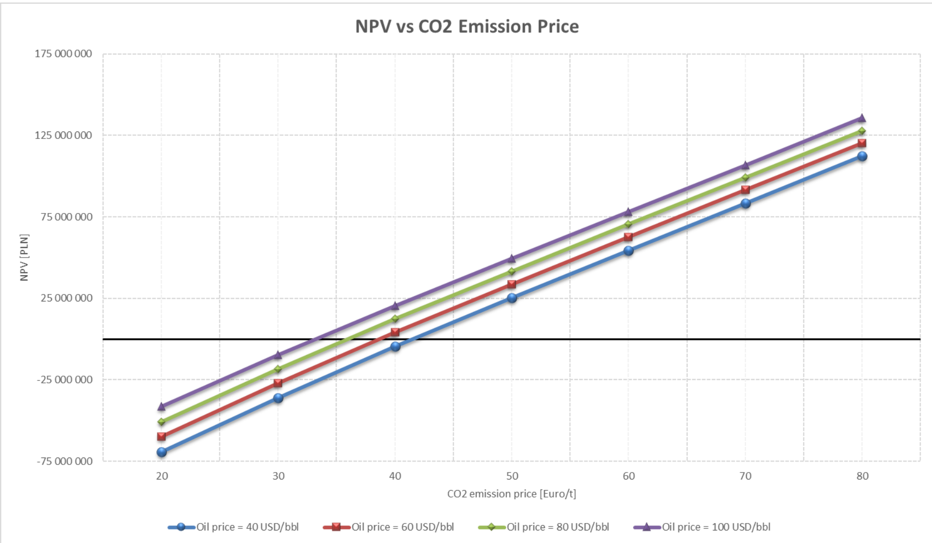

Fig. 6. NPV of combined CO_2-EOR and CCS project vs. carbon allowance and crude oil prices

Capital expenditure, as is usual in the case of petroleum investments, have the biggest impact on NPV. The second most important factor is the price of carbon emissions rights and only in third place, and much less significant, is the price of crude oil. It is clear, in this case, that the key factor influencing the value of NPV is not, as has generally been thought in such projects, the price of oil , but is the cost of carbon emissions rights. As long as these prices are not at a sufficiently high level, one cannot expect the wide development of combined CO_2-EOR and CCS projects, because under current market conditions they will not generate the desired profit.

The second part of the economic analysis was probabilistic and involved estimating the maximum amount of CAPEX (capital expenditure) using the Monte Carlo method which is an

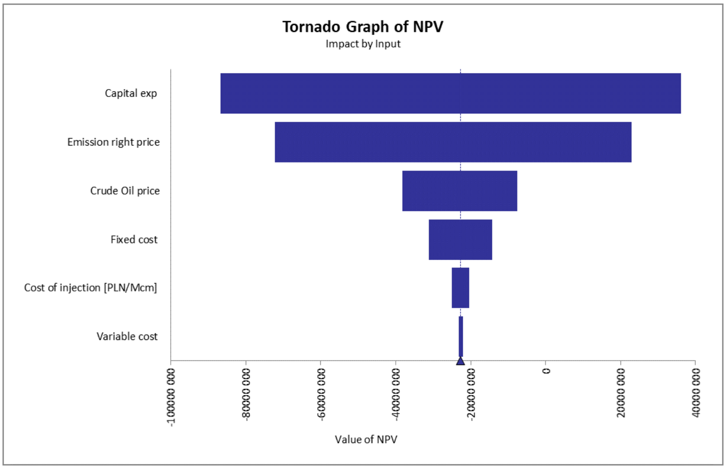

Fig. 7. Sensitivity of the project (tornado graph)

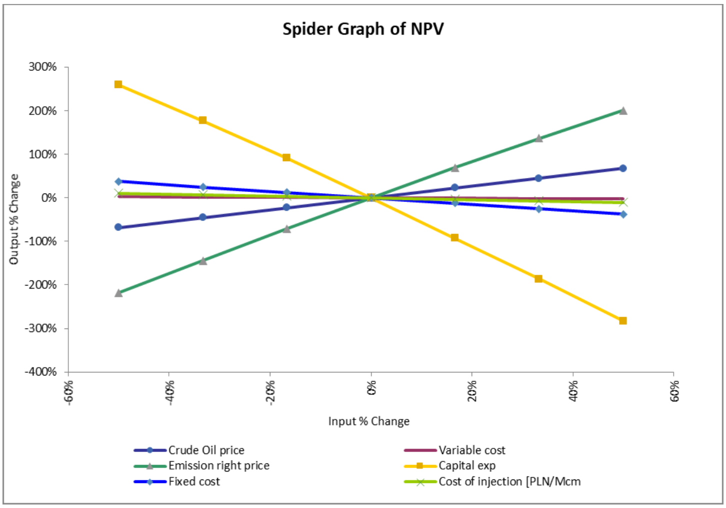

Fig. 8. Sensitivity of the project (spider graph)

example of an alternative approach to investment project assessment. This approach has been applied because very often on the initial stage of an investment project it is difficult to determine the precise value of economic inputs. Therefore, one may want to apply a slightly different method that allows us to make an initial evaluation and selection of the most profitable option without knowing some economic inputs e.g. CAPEX or OPEX (operational expenditures). In this case, the maximum level of CAPEX is sought and it identifies the limit of a project's profitability. If the actual CAPEX value (given that the project is carried out) is lower than that limit, the return on investment will be higher than expected. If not, the value of the project will be lower than anticipated. An understanding of the maximum level of CAPEX for the project's expected profitability, facilitates proper assessment and lets project managers reach profitability during the later stages of the project.

The maximum level of CAPEX is calculated in each iteration of the Monte Carlo (MC) simulation. When values of input parameters are drawn according to their profitability distributions and NPV is calculated, the value of CAPEX which makes NPV equal to zero is found. When NPV value is 0 the internal rate of return (IRR) is equal to the used discount rate. It means that, for CAPEX calculated in such a way, the profitability of the project is identical to the discount rate. The expected profitability of the project was set at the level of 6% annually.

Fig. 9 presents oil price distribution used in our simulation (triangular, min = 45 USD/bbl, most likely = 70 USD/bbl and max = 90 USD/bbl). Fig. 10 shows carbon emission price distribution (triangular, min = 10 €/t, most likely = 20 €/t and max = 60 €/t).

During our economic assessment two cases were examined. In the first the CO_2 emitter pays for CO_2 storage and the price is equal to 80% of carbon emissions rights price (that case is called "storage revenue case"). In the second the emitter doesn't pay for storage (it is called "no storage revenue case"). The level of 80% of carbon emissions rights price was arbitrarily assumed by the Author, because the price for storage has to be lower than carbon emission price (otherwise there is no incentive for CCS) but it also has to be high enough to ensure the profitability of CO_2-EOR and CCS projects.

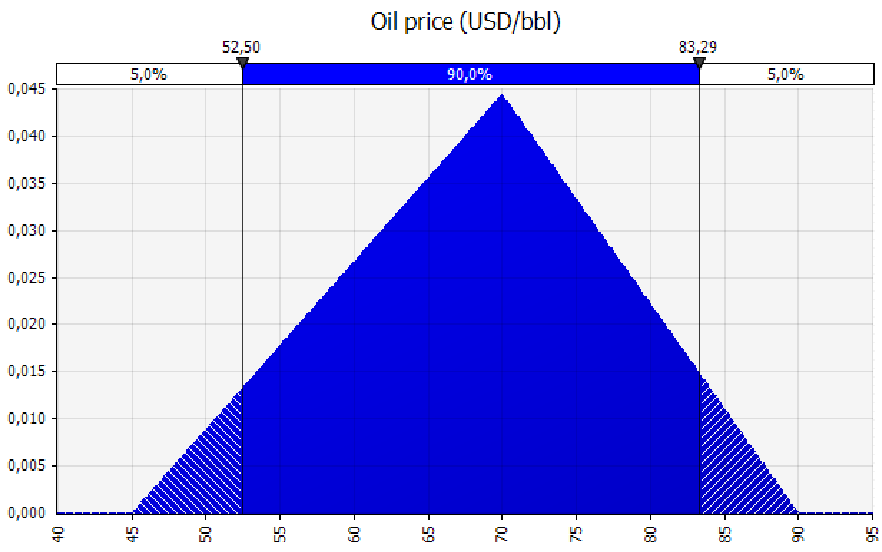

Fig. 9. Oil price distribution used in the MC simulation

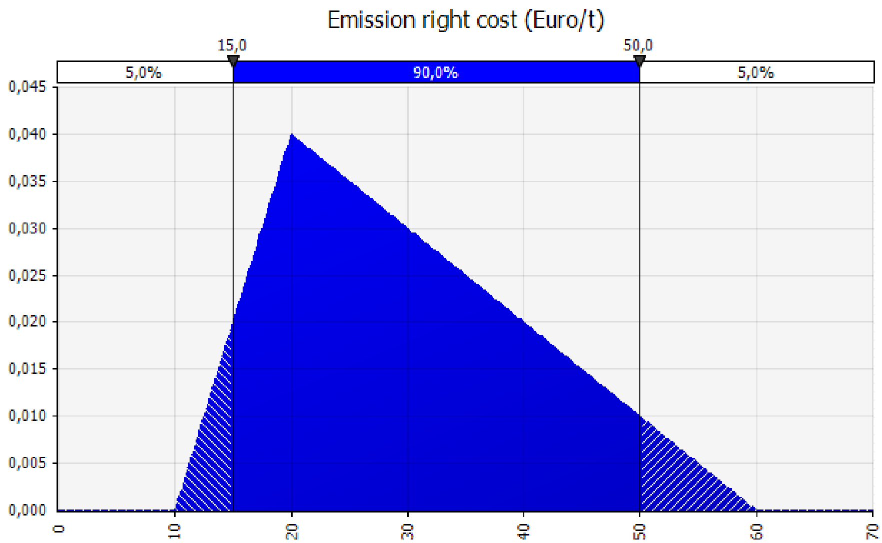

Fig. 10. Carbon emissions rights price distribution used in the MC simulation

Figures 11 and 12 present histogram and distribution function of CAPEX in the storage revenue case. The maximum value of CAPEX giving an IRR equal to 6% remains between 30 and 157 million PLN with a mean value of 82 million PLN. Sensitivity analysis confirms the results achieved in the previous, deterministic approach (Fig. 13). The maximum value of CAPEX is strongly dependent on the price of carbon emissions rights and the oil price is much less significant.

Figures 14 and 15 show histogram and distribution function of CAPEX in the no storage revenue case. When injected CO_2 is not a source of additional income the maximum value of

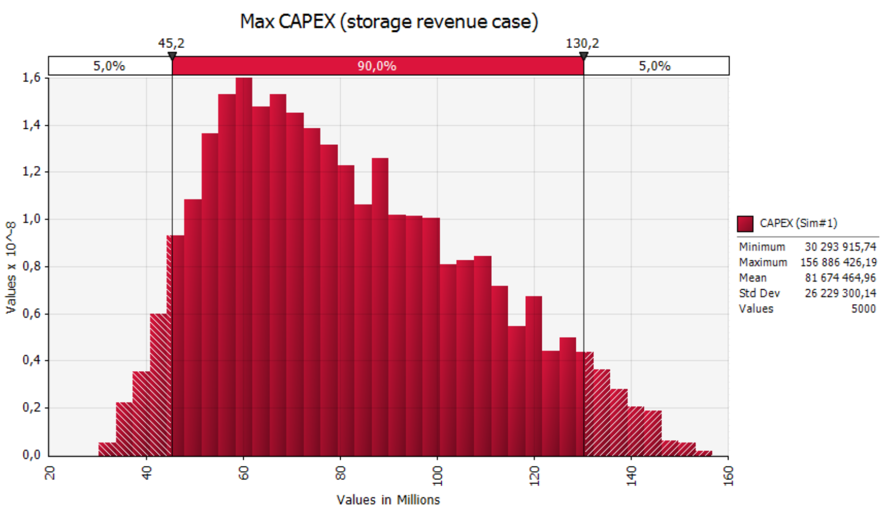

Fig. 11. Histogram of max CAPEX (storage revenue case)

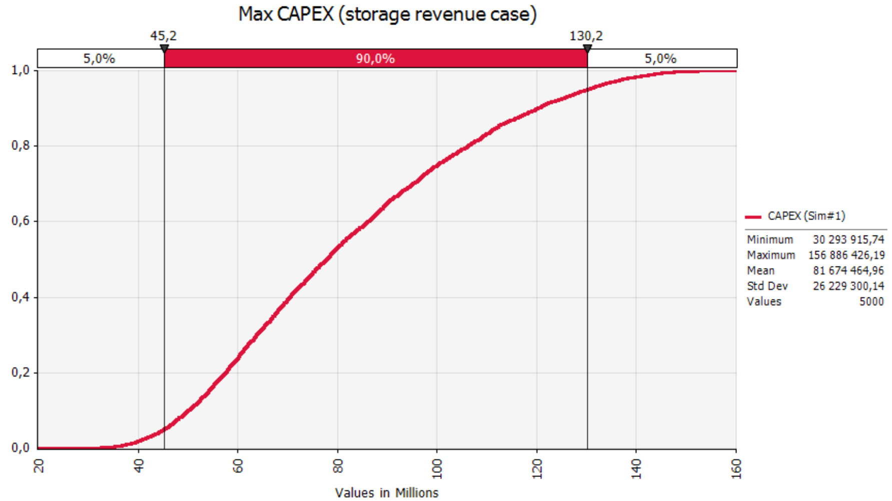

Fig. 12. Distribution function of max CAPEX (storage revenue case)

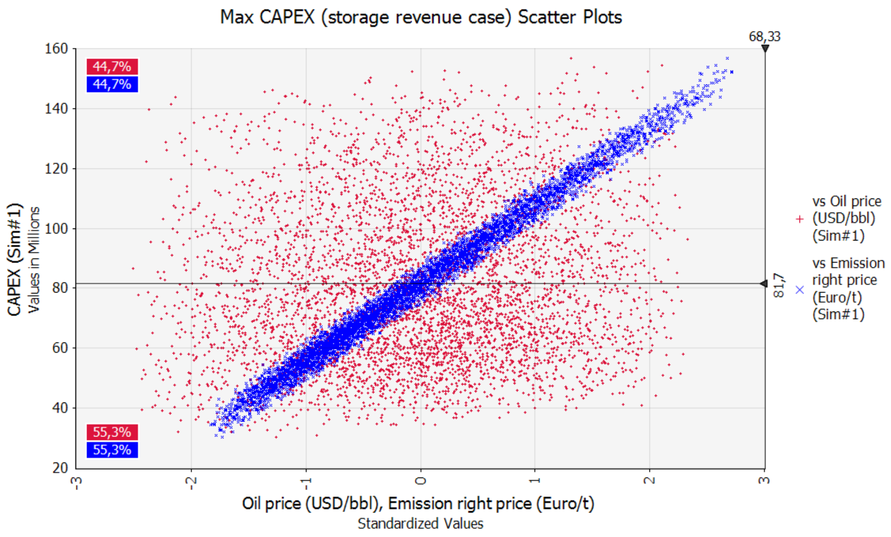

Fig. 13. Max CAPEX vs. oil and emissions rights prices (storage revenue case)

CAPEX is significantly lower and is in the range 0.3 million to 18 million PLN with a mean value of 9 million PLN. It means that such a project is unprofitable, because the estimated value of maximum CAPEX is definitely too low for such a type of investment.

An illustration of the difference between maximum CAPEX for both cases is in Figure 16. It clearly shows the impact of carbon emissions rights price on the investment project. The storage revenue case can be much more profitable than the no storage revenue case. The maximum level of CAPEX is distinctly higher and it makes the investment project more likely to succeed.

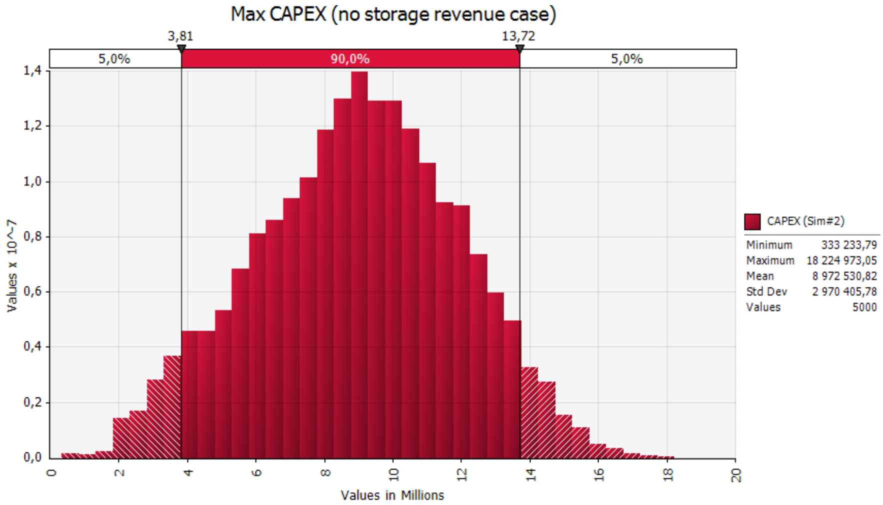

Fig. 14. Histogram of max CAPEX (no storage revenue case)

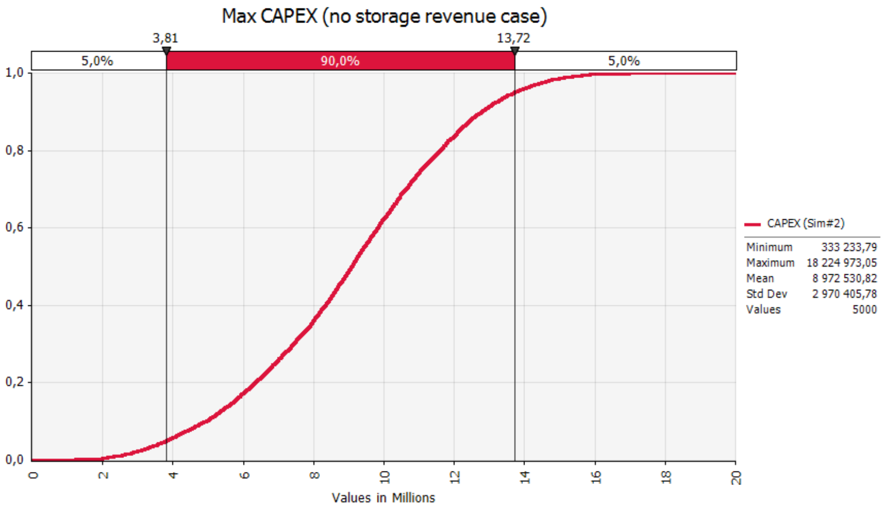

Fig. 15. Distribution function of max CAPEX (no storage revenue case)

4. Conclusion

Enhanced oil recovery (EOR) is a group of various techniques which make possible the production of hydrocarbons left in a reservoir after the primary and secondary exploitation phases. One of them is carbon dioxide enhanced oil recovery (CO_2-EOR). CO_2-EOR method is used to increase oil production by injecting CO_2 into the reservoir but it can be also used as a carbon capture and storage project. Combining CCS with CO_2-EOR may provide an important

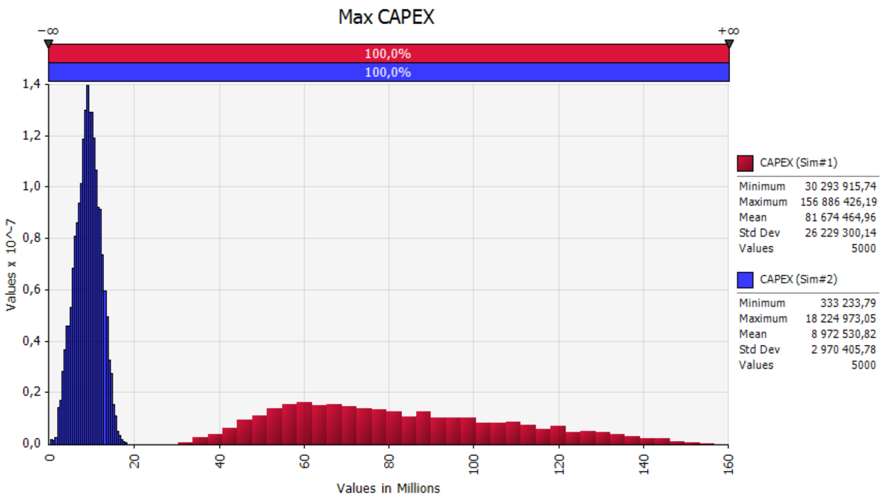

Fig. 16. Maximum CAPEX level for no storage revenue case (left) and storage revenue case (right)

financial incentive, because currently CO_2 is a costly input for CO_2-EOR projects, and therefore the amount of CO_2 is usually economized. However, in the context of carbon emissions policy, such projects may receive additional financial incentives for any CO_2 they sequester. What is more, hydrocarbon reservoirs are good candidates for CO_2-EOR because a lot of geological and production data is available and also most of the infrastructure already exists. One should also bear in mind that such storage sites require monitoring after cessation of operating activities.

In Europe additional income may be generated thanks to the European Emission Trading Scheme (EU ETS). Recently, after a period of long-term stagnation, these prices have started to rise which affects the electricity market in Poland. This can be an important incentive for the development of CCS technology, especially in combination with CO_2-EOR, because in the case of very high prices of carbon emissions rights CCS may turn out to be a cheaper solution for large emitters e.g. electricity and heat producers, chemical plants etc.

In Poland, there are many oil reserves that have been operating for a long time mainly with primary methods. Thank to this, they have great potential for the use of combined CCS and CO_2-EOR. The oil field analyzed in this article is located in southern Poland and contains 8 horizons which are hydrodynamically independent. The 5 shallowest horizons are saturated with oil and the remaining 3 are gaseous. During 15 years of simulated field operation total oil production increased by almost 350% (when compared to the base case without EOR approach). The total volume of injected CO_2 was over 175 million sm^3.

Economic efficiency is the main determinant of the EOR project's success, as well as a very significant factor influencing the potential development of CO_2 underground storage. In standard CO_2-EOR projects the cost of injected CO_2 is a very important limitation, but the combination of such project with CCS can make achievement of the profitability threshold much easier.

Economic analysis of the combined CO_2-EOR and CCS project was divided into two parts. The first used a standard, deterministic approach, based on the DCF method and commonly used NPV. The second part of the economic analysis was probabilistic and involved estimating the maximum amount of CAPEX using the Monte Carlo method.

Results show for the price of carbon emissions rights below €35/t and oil prices in the range of 40-100 USD/bbl such a project is definitely unprofitable. Only a price of carbon emissions rights above €40/t can make it profitable, almost irrespective of the price of oil. This observation is confirmed by the sensitivity analysis of the NPV. Capital expenditures have the biggest impact on NPV but the second most important factor is the price of carbon emissions rights and only in third place, and much less significant, is the price of crude oil. The maximum value of CAPEX is strongly dependent on the price of carbon emissions rights and the oil price is much less significant. The storage revenue case (the emitter pays for CO_2 storage) can be much more profitable than the no storage revenue case because the maximum level of CAPEX is significantly higher and it makes the investment project more likely to succeed.

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